UNIVERSITI PUTRA MALAYSIA

EVALUATION OF TECHNIQUES FOR DETERMINATION OF SATURATED HYDRAULIC CONDUCTIVITY IN THE VADOSE ZONE

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FK 2004 53

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia in Fulfilment of the Requirements for the Degree of Master of Science

June 2004

Abstract of thesis presented to the Senate of Univeresiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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June 2004

Chairman: Professor Ir. Mohd. Amin Mohd. Soom, Ph.D.

Faculty: Engineering

Saturated hydraulic conductivity of a soil (K_s) is a measure of a soil's ability to transmit water in a water-saturated state. Infiltration, drainage, and groundwater pollution are strongly influenced by the magnitude and spatial distribution of the vadose zone field saturated soil hydraulic conductivity (K_{fs}). There are numerous methods of estimating K_s ranging from direct measurement in the laboratory or in situ to models that use only basic soil data (e.g. soil textural classes, bulk density, D_b, organic matter, OM, or porosity, *E*,). However, the results from different measuring techniques vary under different field conditions. In this study of Serdang Series soils found in the Universiti Putra Malaysia (UPM) campus, soil K_s values were collected at different depths using three direct methods. Estimation of K_s were done using six empirical models. The direct methods were in situ techniques of Guelph Permeameter (GP) and double ring infiltrometer (DRI), and constant head permeameters (SCHP), a laboratory technique on intact soil cores

extracted from the same site at different depths. Predictive models included models of Cosby et al. (1984); Brakensiek et al (1984); Saxton et al (1986); Vereecken et al. (1990); Jabro (1992) and Amin et al. (1997). In this study of K_s in the vadose zone, the focus was towards comparison of measurements in the field to those of extracted samples from the same site, but determined by laboratory testing, under controlled condition, and those estimated from empirical models. In addition, a model was developed for determining K_s values based on seven basic soil properties (sand, silt, clay, D_b, moisture content (MC), *E* and OM). The results of the comparison showed that the geometric mean of K_s values obtained by the three experimental methods varied from 7.333 x 10^{-8} to 1.315 x 10^{-2} cm s^{-1} (6.34 x 10^{-5} m / day to 11.36 m / day). The GP method yielded the widest range from 7.333 x 10^{-8} to 1.654 x 10^{-3} cm s^{-1} while the SCHP yielded the narrowest range from 4.4 x 10^{-6} to 1.315 x 10^{-2} cm s^{-1}. Geometric mean K_s values were 27 to 360 times greater for the SCHP compared to the GP method and were significantly different at all depths. Measurements of K_s for the soil under consideration indicate that the DRI and GP methods provided reasonable similar values at the topsoil layer (0-15 cm). While the geometric mean K_s values measured by the DRI method was statistically different from those obtained by SCHP method at 0-15 cm depth.

The laboratory technique yielded greater standard deviation (SD) at the 30 cm and 60 cm depths. Some soil cores may have more macropores than others, whereas the coefficient of variation values were greater for the GP method. The GP produced in situ calculation of K_{fs} in a relatively short time (25 to 90 minutes for a single measurement) compared to DRI (120-180 minutes) and SCHP (1500-1660 minutes).

The results of the multiple regression analysis indicated that the significant inter-correlations limited the number of useful functional relationships that could be derived from the seven variables (Textural classes, D_b, MC, E, and OM). The results of regression for full data set showed that only simple function based on silt content and OM gave a significant relationship with K_s at 0.05 level, but only 10.5 % of variability in K_{fs} was explained by those variables. There was a significant relationship between K_s and the input variables at each depth. These relationships however were different at each depth. The best models found from this study at depth of 0-15 cm, have silt, sand, E, and MC; at depths of 15-30 cm have silt, sand, and E; at depths of 30-60 cm have clay, sand, OM, and MC; and at depths of 60-90 cm silt, D_b and E with values of R^2 = 0.57, 0.50, 0.41 and 0.74, respectively.

In this study the geometric mean error ratio (GMER) and geometric standard deviation error ratio (GSDER) were used to evaluate the applicability of the selected empirical models. The results showed that model of Amin et al (1997) produced noticeably best results with GMER closest to 1 (0.54) and the lowest GSDER (7.64) of the models tested here. This is followed by the Jabro (1992) model with GMER (0.43) and GSDER (10.22), then Brakensiek et al (1984) with GMER (0.43) and GSDER (15.6). It consequently appeared, at least for this soil (Serdang Series), that of the six models compared in this study, the Amin et al model was the model of choice for the prediction of K_s. The second best model was Jabro model whereas the model of Brakensiek et al. ranked third.

Comparison between the methods was hampered by a number of factors. It was difficult to discriminate between spatial variables of K_s and errors related to the methods. Different sample volumes and sample numbers were used. Comparisons made between different K_s measurements in the field are subject to natural soil variations that may be larger than the differences between methods. Findings of this study can be used as a guideline for application of these methods particularly to the same soil type and depth setup. The correct use of any of these methods for one of the most extensive and productive soils in Selangor (Serdang Series) could be highly beneficial to the agricultural sector.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

PENINAIAN TEKNIK UNTUK MENENTUKAN KEBERKONDUKAN HIDRAUL TEPU DALAM ZON VADOS

Oleh

ABDOLHAKEM O MOHAMED

Jun 2004

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Ketertelapan tepu tanah (K_s) adalah ukuran kemampuan tanah untuk mengalirkan air dalam keadaan tepu. Penyerapan, saliran dan pencemaran air bawah tanah sangat dipengaruhi oleh magnitud dan taburan spatial dilapaugan ketertelapan tepu tanah (K_{fs}) dalam zon vados. Adà beberapa kaedah bagi menganggarkan K_s, antaranya ukuran terus dalam makmal atau di situ dan menggunakan data asas tanah seperti tekstur, ketumpatan (D_b), bahan organik (OM) dan Keliangan tanah (E). Walau bagaimanapun, keputusan yang diperolehi adalah berbeza hasil daripada perbezaan teknik pengukuran dan perbezaan keadaan lapangan. Dalam kajian ini, ujikaji dan ramalan K_s siri tanah Serdang yang terletak di kampus UPM telah dibuat mengikut kedalaman tiga kaedah terus dan enam model ramalan. Kaedah terus mengikut Guelph permeameter (GP), infiltrometer gegelung kembar (DRI) suatu teknik di situ, dan permeameter turus tetap (SCHP), suatu teknik makmal ke atas teras tanah yang tidak diganggu dan diperolehi di kawasan yang sama pada kedalaman yang berbeza. Sementara model ramalan termasuk model

Cosby et al. (1984), Brakensiek et al. (1984), Saxton et al. (1986), Vereecken et al. (1990), Jabro et al. (1992) dan Amin et al. (1997). Objektif utama kajian ke dalam zon vados ini ialah untuk membandingkan K_s di lapangan yang disetkan dengan sampel yang diperolehi di lapangan yang sama, tetapi ditentukan oleh ujian makmal, dan juga ramalan model empirikal. Selain daripada itu, untuk membangunkan sebuah model bagi menentukan nilai K_s berdasarkan tujuh data asas tanah (pasir, kelodak, tanah liat, ketumpatan pukal, kandungan kelembapan, keliangan dan bahan organik). Keputusan perbandingan ujikaji menunjukkan nilai purata geometrik K_s oleh tiga kaedah eksperimen berbeza dari 7.333×10^{-8} hingga 1.315×10^{-2} sm s^{-1} (6.34×10^{-5} m/hari hingga 11.36 m/hari). Kaedah GP pula menghasilkan jarak nilai paling kecil iaitu 7.33×10^{-8} hingga 1.654×10^{-4} sm s^{-1}, sementara SCHP jarak nilai paling besar iaitu dari 4.4×10^{-6} hingga 1.315×10^{-2} sm s^{-1}. Purata nilai geometrik K_s adalah 27 hingga 360 kali lebih besar bagi SCHP berbanding kaedah GP dan adalah berbeza secara bererti untuk semua kedalaman. Kajian ini juga menunjukkan nilai K_s yang diukur oleh kaedah DRI adalah tidak berbeza secara statistik dengan nilai yang diperolehi oleh kaedah GP pada kedalamam 0-15 sm tetapi berbeza secara statistik dengan yang diperolehi daripada kaedah SCHP.

Teknik makmal menghasilkan sisihan piawai (SD) yang lebih besar pada kedalaman 30 dan 60 sm. Kemungkinan ada teras tanah mempunyai lebih banyak rongga daripada yang lain, sebaliknya nilai pekali perbezaan (CV) adalah lebih besar untuk kaedah GP. Kaedah GP menghasilkan anggaran pengiraan K_{fs} di situ dalam masa yang singkat secara relatif (35 hingga 90 minit untuk satu pengukuran) berbanding dengan DRI (120-180 minit) dan SCHP (1500-1660 minit).

Keputusan analisis lebih daripada satu regresi menunjukkan keberertian saling perhubungan menghadkan nilai fungsi perhubungan yang mungkin timbul daripada tujuh pembolehubah (kelas tekstur, D_b, MC, E, dan OM). Keputusan regresi untuk semua set data menunjukkan hanya satu fungsi mudah berdasarkan kandungan kelodak memberikan hubungan bererti dengan K_s pada tahap 0.05 tetapi hanya 10.5 % daripada keberubahan dalam K_{fs} yang diperihalkan oleh keberubahan itu. Keputusan analisis regresi juga menunjukkan ada keberertian perhubungan antara K_s dan input keberubahan setiap kedalaman. Perhubungan ini walau bagaimanapun adalah berbeza mengikut kedalaman. Model terbaik yang ditemui dalan kajian ini pada kedalaman 0-15 sm, mempunyai kelodak, pasir, E dan MC; pada kedalaman 15-30 sm mempunyai kelodak, pasir, dan *E*, pada kedalaman 30-60 sm mempunyai tanah liat, pasir, OM, dan MC;pada kedalaman 60-90 sm mempunyai kelodak, D_b dan *E* dengan masing-masing nilai R^2=0.57, 0.50, 0.41 dan 0.74.

Dalam kajian ini purata kadar ralat geometri (GMER) dan kadar ralat sisihan piawai (GSDER) digunakan untuk menilai kebolehgunaan kaedah model ramalan yang telah dipilih. Keputusan kajian ini menunjukkan model Amin et al. (1997) menghasilkan keputusan terbaik dengan GMER menghampiri 1 (0.54) dan GSDER (7.64) terendah diikuti oleh model Jabro (1992) dengan GMER (0.43) dan GSDER (10.22) dan seterusnya Brakensiek et al. (1984) dengan GMER (0.43) dan GSDER (15.6). Dalan kajian ini setelah perbandingan dibuat ke atas enam model untuk tanah siri Serdang, model Amin adalah model yang dipilih untuk menganggarkan nilai K_s. Model kedua terbaik adalah model Jabro sementara model Brakensiek adalah yang ketiga.

Perbandingan antara kaedah telah dihalang oleh beberapa factor. Adalah susah untuk membezakan keberubahan K_s secara spatial dan ralat yang berkait dengan kaedah yang digunakan dan perbezaan isipadu sampel serta bilangan sampel. Perbandingan dibuat antara perbezaan ukuran dalam lapangan adalah bergantung kepada perbezaan semulajadi tanah yang mungkin lebih besar daripada perbezaan antara kaedah. Keputusan daripada kajian ini memberikan panduan awal menggunakan kaedah-kaedah tersebut khasnya pada tanah yang sama dan kedalaman yang ditentukan. Kaedah yang paling sesuai untuk menentukan K_s bagi sejenis tanah yang paling prodiktif di sekitar Siri Serdang amatlah berguna kepada sektor pertanian.

ACKNOWLEDGEMENTS

First and foremost, all praise be directed to Allah (SWT) for making all things possible, Alhamdulillah.

I would like to express my sincerest thanks to my supervisor, Professor Ir. Dr. Mohd. Amin Mohd. Soom, for his invaluable help, guidance, advice, support and encouragement throughout this work. I also wish to thank Dr. Abdul Aziz Zakaria and Associate Professor Kwok Chee Yan for serving as members of the supervisory committee and for their guidance and valuable suggestions.

Special thanks are extended to Mr. Ghazali Kassium (technicians of Soil and Water lab) for his constant assistance. I wish to express my gratitude to my friends in the faculty of engineering for their help and support, especially Associated Prof. Dr. Abdel Maged Hamuda , Mr Meh Awang, Mr. Johari , and Mr Tajul Ariffin Tajuddin . Special thanks are extended to my best friends Dr. Radim Dadang and Dr. Ahmed Ganfoud for their support.

I am grateful to the People of Libyan Arab Jamahiriya and Omer Al-mukhtar University who provided me the scholarship for pursuing the Master degree at Universiti Putra Malaysia. Also, I would like to express my gratitude to Univeristi Putra Malaysia for some financial support to the study.

I would like to express my heartfelt thanks to all members of my family for their encouragement and overwhelming support to complete this study.

I certify that an Examination Committee met on 14th June 2004 to conduct the final examination of Abdolhakem O. Mohamed on his Master of Science thesis entitled "Evaluation of Techniques for Determination of Saturated Hydraulic Conductivity in the Vadose Zone" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or currently submitted for any other degree at Universiti Putra Malaysia or other institutions.

ABDOLHAKEM O. MOHAMED

Date: 06 September 2004

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LIST OF SYMBOLS

Symbol	Description	unit
D_b	Bulk Density	$g\ cm^{-3}$
D_p	Real Density	$g\ cm^{-3}$
ρ_L	Liquid density	$g\ cm^{-3}$
η	Dynamic viscosity	poise
Q_s	Steady Discharge	$cm^3\ s^{-1}$
Q_{s1}	Steady Discharge at hydraulic head (H_1)	$cm^3\ s^{-1}$
Q_{s2}	Steady Discharge at hydraulic head (H_2)	$cm^3\ s^{-1}$
K	Hydraulic conductivity	$cm\ s^{-1}$
k'	Intrinsic permeability	cm^{2}
K_s, K_{sat}	Saturated hydraulic conductivity	$cm\ s^{-1}$
K_{fs}	Field Saturated Hydraulic Conductivity	$cm\ s^{-1}$
K_{sGM}	Geometric mean saturated hydraulic conductivity	$cm\ s^{-1}$
K_{sMax}	Maximum saturated hydraulic conductivity	$cm\ s^{-1}$
K_{sMin}	Minimum saturated hydraulic conductivity	$cm\ s^{-1}$
K_{sH}	Horizontal saturated hydraulic conductivity	$cm\ s^{-1}$
K_{sV}	Vertical saturated hydraulic conductivity	$cm\ s^{-1}$
i	The hydraulic or potential gradient	
g	Acceleration due to gravity	$cm\ s^{-1}$
α^*	Sorptive number	cm^{-1}
ϕ_m	Matric flux potential	$cm^2\ s^{-1}$
q_x, q_y, q_z	Infiltration flux through (x, y, and z) directions	$cm\ s^{-1}$
H	Depth of water level in the borehole	cm
H	Hydraulic Head	cm
h	Depth of water ponded at soil core surface	cm
I_R	Infiltration Rate	$cm\ h^{-1}$
I_C	Final infiltration rate	$cm\ h^{-1}$
Z	Measured cumulative infiltration	cm
OM	Organic Matter	%
MC	Soil moisture content	%
E	Porosity	%
N	Number of samples or observations	
L	Length of the intact sample	cm
A	Cross-section area of the core or brass ring	cm
D	Internal diameter of the brass ring	cm
a	Radius of the brass ring	cm
V	Volume of the cylindrical core	$cm\ s^{-3}$
h	length of the cylindrical core	cm
t	Time	s
W_s	Weight of the air dry soil	g
R	Rate of fall of water level in GP reservoir	$cm\ s^{-1}$
CV	Coefficient of variation	%
SD	Standard deviation	

R^2	Coefficient of multiple determination
r	Correlation coefficient
V	variance
S	Sand
Si	Silt
C	Clay
SE	Simultaneous Equation analysis
SH	Single Head analysis
GP	Guelph permeameter method
CHWP	Constant Head Well Permeameter method
SCHP	Constant Head Permeameter method
AH	Auger hole method
DRI	Double Ring Infiltrometer method
RI	Ring Infiltrometer
IPM	Instantaneous profile method
DTM	Double Tube Method
WP	Well Permeameter
SWPT	Shallow Water Permeameter Technique
SI	Sprinkler infiltrometer
TI	Tension infiltrometer
FI	Furrow infiltrometer
GI	Guelph infiltrometer
PM	Predictive Model
PTF	Pedotransfer function
H_2O_2	Hydrogen peroxide %
GMER	Geometric mean error ratio
GSDER	Geometric standard deviation of error ratio
PSD	Particle-size distribution
RMSE	Root mean squared error
RMSR	Root mean squared of residuals
RMSD	Root mean squared deviations
UPM	Universiti Putra Malaysia.
FAO	Food Agricultural Organization
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture

CHAPTER I

INTRODUCTION

General

Water movement in soils whether under the saturated or unsaturated conditions is highly dependent on the hydraulic conductivity (K) of the soil. For a given soil, K is defined as a constant that relates the rate of water transport in that soil to the hydraulic gradient or driving force causing water to move. Under saturated c ondition it i s called saturated hydraulic conductivity and generally is denoted by K_s, or K_{sat}, while under unsaturated condition it is referred to as unsaturated hydraulic conductivity. Qualitatively, K is the ability of the soil to transmit water and generally speaking, is a maximum at saturation but under unsaturated condition its value however, have been found to decrease dramatically with decreasing water content.

Vadose zone soil saturated hydraulic conductivity, K_s, is the volume of water, which will pass through a unit cross-sectional area of a soil above the water table in unit time, given a unit difference in water potential. Its behavior plays a crucial role in modeling water flow and chemical transport in the saturated media. It is perhaps one of the most important hydraulic properties used by hydrologist, water resources engineers, and environmental soil scientists to solve many agricultural and hydrological and environmental problems. Soil's K_s values have an important application in areas ranging from the analysis of any saturated-soil